Contract # N00014-14-C-0020

Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area "Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft". The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure) significant aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech's flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

Activities this period

During this report period, we implemented the CRAFT CFD code on the Penn State VLRCROE Flight simulator and performed the first Pilot-in-the-Loop PILCFD tests at Penn State using the COCOA5 clusters. The initial tests were performed with 1.2 million grid cells using 640 processors. The tests verified that the network configuration works and demonstrated the integration of the flight simulator and Penn State computing infrastructure. Initial tests showed slower performance than real-time (3x slower than real-time). In order to investigate our system performance and to figure out drawbacks of using relatively coarse computational domains to reach real-time speeds, additional fully coupled simulations were performed. The results showed us the sensitivity of the dynamic response of the helicopter to coarseness of the mesh used.

PILCFD Simulations at Penn State VLCROE Flight Simulator

The initial PILCFD efforts were performed early in 2016 at CRAFT Tech's facility and results were presented at AHS Forum 72 (Ref 1) All these efforts performed on CRAFT Tech's in-house cluster with 32 nodes each containing 8 Intel Xeon E5530 Processors (2.4 GHz), using a 40Gpbs Inifiniband interconnect (32 nodes x 8 procs =256 processors). As a flight platform, a workstation running XPlane with a simple joystick was used (Figure 1). At that time, we were able to demonstrate the first near-real-time (3x slower) PILCFD test for a simplified shedding wake using a 300K grid cells and inviscid flow assumption.

Figure 1 – Initial near-real-time PILCFD test was performed at CRAFT Tech in early 2016.

During this reporting period, we implemented the CRAFT CFD code on the Penn State computing infrastructure (COCOA5) and integrated the COCOA5 cluster with the VLRCOE Flight simulator (Figure 2). The Penn State VLCROE Flight simulator cab is from the historic XV-15 tilt rotor aircraft. A four-channel Control Loading System provides fully programmable high bandwidth control loading and reads the pilot stick positions. The simulator integrates up to eight different computers on a local network to distribute the computing load, with separate computers providing Image Generation, interface with the control loading system, cockpit instrument displays, and the math model of the rotorcraft dynamics. The visual system consists of a three-channel high-resolution projection system (WSXGA+ native resolution), a 15' diameter by 11'-high cylindrical screen, and image distortion correction and blending. This provides a seamless 170° horizontal field-of-view. The X-Plane Professional flight simulation software is used for Image Generation, with three separate computers driving each visual channel. The COCOA5 cluster is made up of a single master node and 47 computational nodes built on the 7th generation of Proliant Servers from HP. Each computational node is built on the DL165 platform and uses two AMD 6276 "Interlagos" 16-core processors, 32 cores per node, at 2.3 GHz (1,504 cores in total)(introduced in Nov 2011). The network communication between nodes is established using a low latency 20 Gb/s Infiniband fabric.

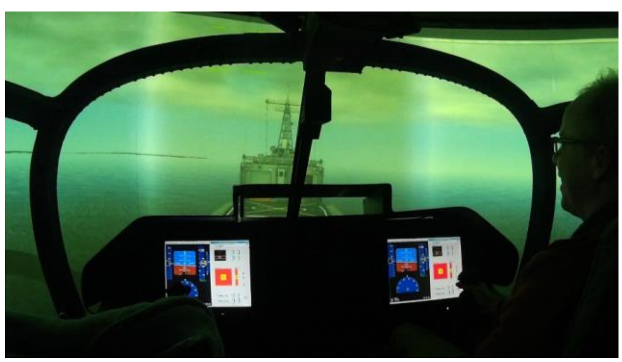


Figure 2 – First PILCFD test at Penn State VLRCOE flight simulator facility

Towards the real-time PILCFD simulations we conducted several efforts at Penn State. The initial efforts showed that the network configuration (Figure 3) between the flight simulator and the computing cluster (COCOA5) works well. In contrast to our first PILCFD efforts at Craft Tech's facility, this time a relatively finer mesh with 1.2 million grid cells was used to resolve the same simplified shedding wake using a viscous flow assumption with no turbulence model. The resolved scales of turbulence modeled using Monotone Integrated Large Eddy Simulation (MILES), which has been shown to be adequate for airwake simulations and reduces the computational cost of the simulations (Ref 2).

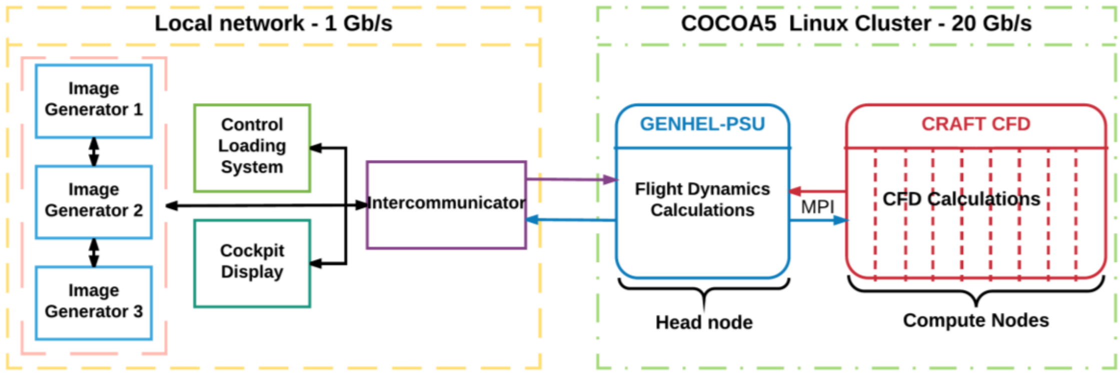


Figure 3 – PILCFD demonstration case network configuration used for Penn State Flight Simulator

Figure 4 shows the dynamic response of the simulated helicopter during the first PILCFD test at Penn State VLRCOE flight simulator. The pilot performed a simple approach case during the test. The flight simulator was fully coupled with the CFD simulation, which was running on 640 processors at COCOA5 cluster. The achieved average execution time of the simulation was 3 times slower than real-time.

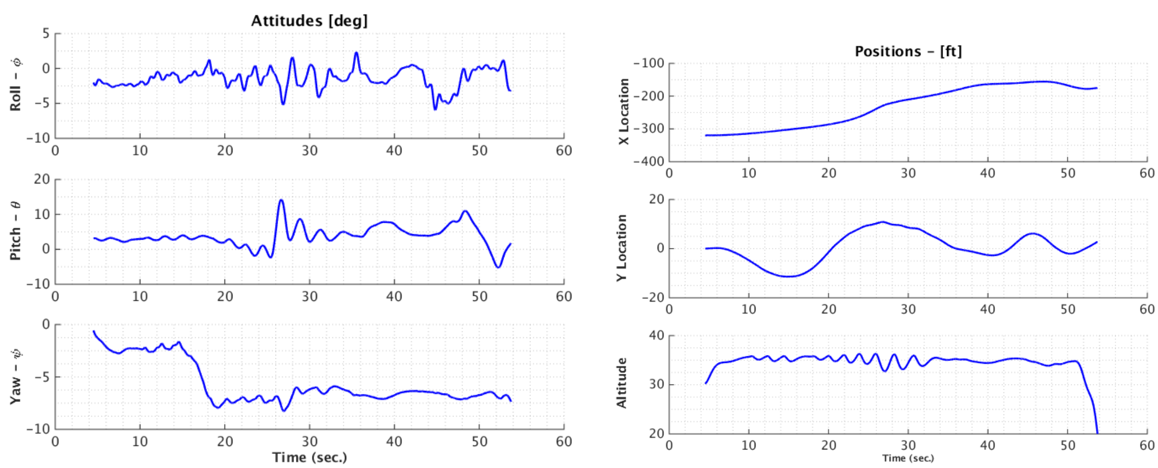


Figure 4 – The changes in dynamic response of the helicopter during first PIL-CFD simulation at Penn State VLRCOE Flight Simulator.

Performance Study and Grid Dependency

To quantify the timing performance of the developed coupling tool on different number of processors, a study was performed to demonstrate the average runtime costs achieved from three different computational domains. For this study, two different flight maneuvers were chosen: Hover in an open domain and approach to a simple backward-facing step. For each case, three different computational domains with different mesh resolutions at the rotor region were prepared. For the hover case, the computational grid sizes were: 550k, 700k, 5.98m while the mesh resolutions were 4ft., 2ft. and 1ft. respectively. For the approach case, the computational domain sizes were: 330k, 1.2m, 8m, while the grid resolutions at the rotor disk region were 4ft, 2ft and 1ft respectively.

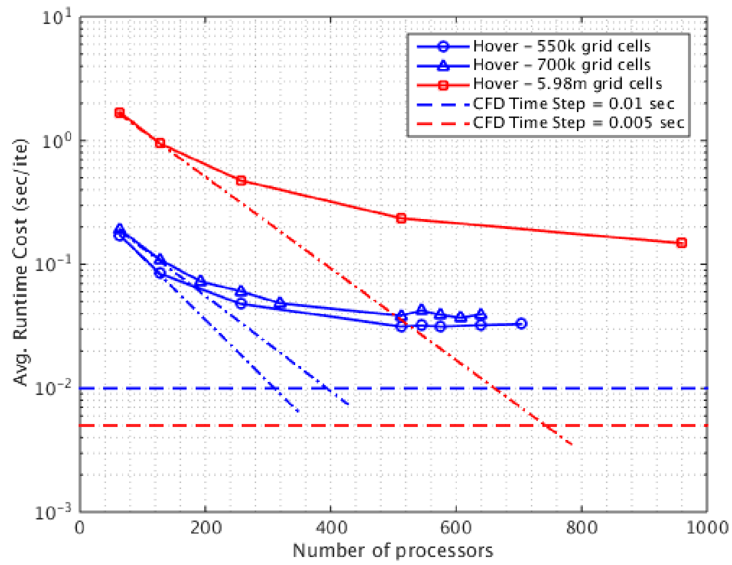


Figure 5 - Average runtime cost achieved from each of the computational grid used for the hover case, running on different number of processors.

Figure 5 shows the average runtime achieved from each of the computational grid used for the hover case, running on different number of processors. All these simulations were performed using a NLDI controller to keep the helicopter at the desired position. For the 550k and 700k cases, the CFD time step was set to 0.01 and for the 5.98m case, the CFD time step was set to 0.005 seconds.

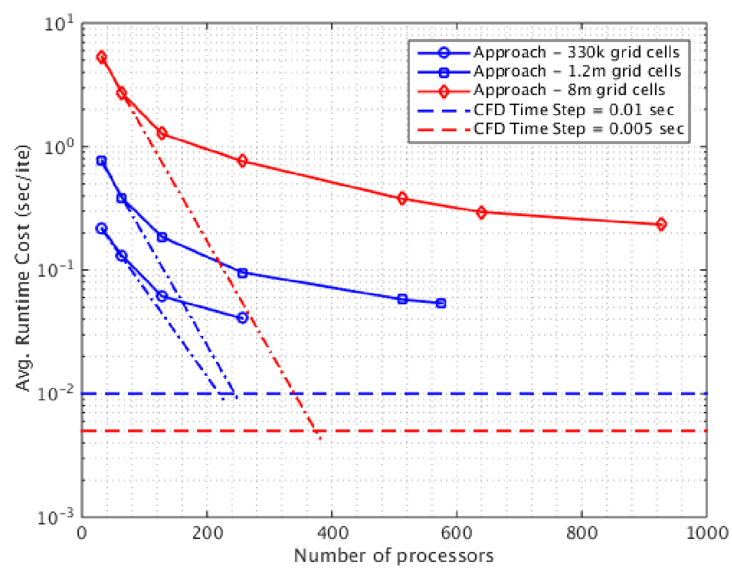


Figure 6 - Average runtime cost achieved from each of the computational grid used for the approach case, running on different number of processors.

Figure 6 shows the average runtime achieved from each of the computational grid used for the approach case, running on different number of processors. Similar to the hover case, all these simulations were performed using a NLDI controller to keep the helicopter at the desired flight trajectory. For the 330k and 1.2m cases, the CFD time step was set to 0.01 sec and for the 8m case, the CFD time step was set to 0.005 seconds.

As it can be seen from Figure 5 and Figure 6, the execution times do not drop in exact proportion to the increase in number of processors. Parallel efficiency of a PDE solver depends on several factors such as partitioning algorithm, algorithmic scalability and load balancing. On a scalable implementation, the time per iteration is expected to reduce in inverse proportion to the number of processor (Ref 3). Prior scalability tests with standalone CRAFT CFD solver showed better performance than these results. The reason of poor scalability on the coupled simulations may be the earlier coupling interface implementations on the CFD solver. For example, currently, the source point search task is performed in parallel (to the solver tasks) on a single processor. As the CFD is partitioned into larger numbers of processors, the point search task cost will remain the same, and may become a larger and larger percentage of the cost. This may results in a poor load-balancing in the simulation and a stall on the solver scalability performance.

Table 1 – Achieved minimum execution times for each of the computational domain.

Case	Number of processor used	CFD time step (sec)	Achieved minimum execution time (sec/ite)	Real-time performance
Hover – 550k	704	0.01	0.033	3.3x slower
Hover – 700k	640	0.01	0.0395	3.9x slower
Hover – 5.98m	960	0.005	0.148	29.6x slower
Approach – 330k	256	0.01	0.0408	4.08x slower
Approach – 1.2m	604	0.01	0.0519	5.19x slower
Approach – 8m	928	0.005	0.215	43x slower

Figure 7 to Figure 10 show the variations in the dynamics response of the simulated helicopter approaching to a backwards-facing step. The “No-coupling” case represents the standalone GENHEL-PSU simulation without any airwake disturbance. The remaining simulations represent the fully coupled simulations performed with different computational domains. Results show that the fully coupled simulation using the 4ft mesh resolution at the area of interest shows the least airwake disturbance. The coarse mesh structure results in very high dissipation in the flow solution and creates only minor disturbances on the helicopter body. On the 1.2m and 8m cases, we get better results than the 330k case. The airwake intensity is relatively higher and which results in more fluctuation in the helicopter dynamic responses. The fluctuations are similar for the first half of the simulation, when the helicopter is far behind the box structure. However, results are different when the helicopter gets close the box structure, where the flow shows more chaotic behavior.

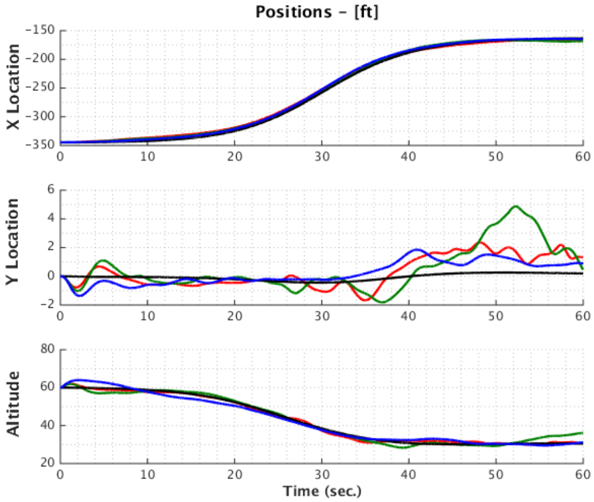


Figure 7 – Variations in the positions of the simulated helicopter.

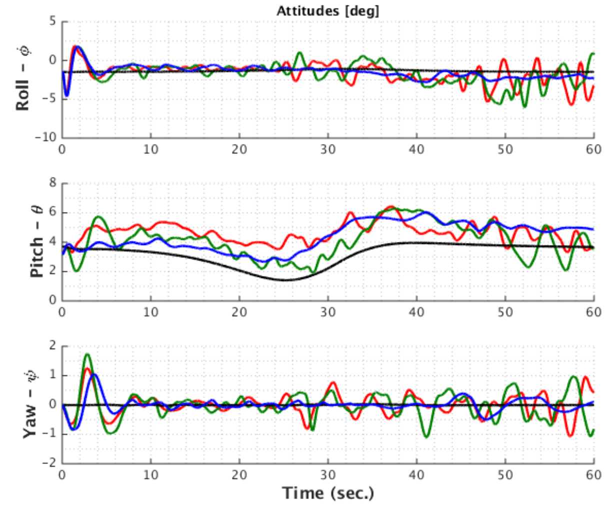


Figure 8 – Variations in the attitudes of the simulated helicopter.

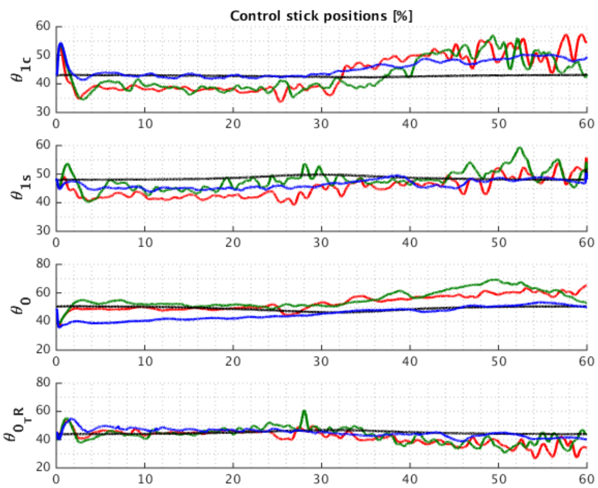
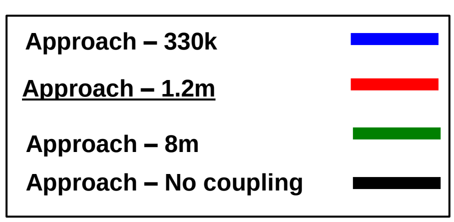


Figure 9 – Variations in the control inputs of the simulated helicopters.

Figure 10 – Variations in the total power required of the simulated helicopter.



Significance of Results

The CRAFT CFD code was successfully implemented to the Penn State VLRCROE Flight simulator and first Pilot-in-the-Loop CFD (PILCFD) tests were performed at Penn State using COCOA5 clusters. The initial tests were performed with 1.2 million grid cells using 640 processors and showed 3 times slower performance than real-time on the COCOA5 clusters. We verified that the network configuration works well and we are able to perform PILCFD test using the actual flight simulator and Penn State computing infrastructure. Note that COCOA5 uses relatively old architecture, which is almost 6 years old. We are currently building a new cluster system at our department and our initial tests with the new built cluster system (COCOA6) which showed almost 2x faster performance than then COCOA5. Additionally, we investigated the timing performance of the CFD solver on different number of processors for two different cases and using three different mesh resolution of for each case. Initial test results showed the limitations of the CFD solver scalability with the increasing number of processors as a result of the latest coupling interface implementations on the code. We will perform further study to investigate these limitations.

2. Plans and upcoming events for next reporting period

- We are performing additional tests to quantify the timing performance of the CFD solver. We plan to repeat PILCFD tests using the actual flight simulator and different computational domains. Results will help us to figure out the potential speed up gains by optimizing grid that we used for the simulation.

- We will be collaborating with Craft-TECH to discuss scalability issues of the CFD solver and seek possible improvements. Initial test results showed the limitations of the CFD solver scalability with the increasing number of processors as a result of the latest coupling interface implementations on the code. We will perform further study to investigate these limitations.

3. References

[1] Oruc, I., Shenoy, R., Shipman, J., and Horn, J.F., "Toward Real-time Fully Coupled Flight Simulations of the Helicopter/Ship Dynamic Interface," American Helicopter Society Forum 72, West Palm Beach, FL, May 2016.

[2] S.A. Polsky, C.W. Bruner, "Time-Accurate Computational Simulations of an LHA Ship Airwake," Paper AIAA-2000-4126, 18th AIAA Applied Aerodynamics Conference, Denver, CO, August 2000.

[3] Gropp, W. D., D. K. Kaushik, D. E. Keyes, and B. F. Smith. "Understanding the parallel scalability of an implicit unstructured mesh CFD code." work 7 (2000): 6.

4. Transitions/Impact

No major transition activities during the reporting period.

5. Collaborations

CRAFT Tech made a visit to Penn State during this reporting period. We have performed the first PILCFD tests together and discussed the potential efficiency improvement on the coupling interface.

The work continues to involve close collaboration between PSU, CRAFT-Tech, and NAVAIR.

6. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

7. Publications

Oruc, I., Horn, J.F. and Shipman, J., “Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions,” AIAA Journal of Aircraft. (This journal paper is accepted and in publication process.)

Oruc, I., Shenoy, R., Shipman, J., and Horn, J.F., “Toward Real-time Fully Coupled Flight Simulations of the Helicopter/Ship Dynamic Interface,” American Helicopter Society Forum 72, West Palm Beach, FL, May 2016.

Oruc, I., Horn, J.F., Shipman, J., and Shenoy, R., “Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions,” AIAA Modeling and Simulation Technologies Conference, AIAA SciTech, San Diego, CA, January 2016.

Oruc, I., Horn, J.F., Polsky, S., Shipman, J. and Erwin, J., “Coupled Flight Dynamics and CFD Simulations of the Helicopter/Ship Dynamic Interface”, American Helicopter Society Forum 71, Virginia Beach, VA, May 2015.

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